Chapter 4

Characterization and Categories of Aquaculture Production Systems

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The basic progression of this chapter, and this book, is from less intensive production systems to more intensive production systems. For aquaculture, intensification implies a number of things. One factor is how densely the animals are stocked into the system. For reservoir ranching systems, there may be 10 kg of animals in a hectare (10 kg/ha) while in intensive recirculating heterotrophic systems, there may be 10 kg of animals in *one square meter* (or 100,000 kg/ha).

Intensification also implies human intervention and outside inputs into the production system. For example, in some shellfish systems the primary intervention is to add hatchery-reared juveniles into the natural ocean habitat or to add some additional substrate for the shellfish to grow on. This is in contrast to an intensive recirculating system where the aquaculturist must provide for almost every biological function—including the oxygen for the animals to breathe.

Quite often, intensification also implies energy inputs. As we move up the scale of intensification the amount of energy invested in each kilogram of production also tends to increase. First we add aeration, then we add pumps and filters, and then we begin to add heat. In times of instability in the energy markets, these costs could become even greater considerations. A comparison of the same fish raised in two different systems can illustrate this. Carp raised in ponds with fertilization and limited feeding require 11 gigajoules (GJ) of energy input per ton of edible protein produced, while the same fish raised in a recycle system

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requires 56 GJ of energy input per ton of edible protein produced (De Silva & Soto 2009).

Within this continuum of increasing intensity we have three major categories or classifications for aquaculture production systems. These groupings are primarily based on the amount of control or intervention the aquaculturist provides in terms of the three basic functions or ecosystem services that each system must provide: proper temperature, adequate oxygen, and waste removal. Again, with these classifications we progress from lower inputs and outputs to greater inputs and outputs. However, the demarcations between these systems are not always clear and distinct. These are general categories and there are gradations and overlaps between categories. There are even hybrids among and between these categories.

4.1 Open systems

Production systems within this category rely entirely on natural ecological processes to address the three major functions. These systems are normally natural bodies of water that are now being stocked for commercial production. Many of these systems could be considered stock enhancement rather than aquaculture. Biomass densities are usually low enough that natural processes can provide sufficient oxygen for the biomass being supported. The oxygen can be sourced from diffusion, photosynthesis by natural algal communities, or both. Waste products are also removed by natural processes within the systems operating at natural rates. Bacterial breakdown of solid wastes is by heterotrophic bacteria and fungi. Nitrogenous waste products, such as ammonia excreted by the animal, are either flushed away or processed into less toxic forms by the chemoautotrophic components of the natural nitrogen cycle (nitrification) or assimilated by algae. Water temperatures in these systems are ambient. In open systems, site selection is the major control factor the producer has for all environmental services. Because of this, GIS technologies have in recent years become major tools in identifying and evaluating suitable production locations.

Many production methods in open systems rely on natural water movement from tides, currents, or wind action to move waste products away from the animals and bring new, clean, and highly oxygenated water to the animals. To some extent, stocking rate, and sometimes added substrate, are the only management inputs. Production methods that function in an open system environment include shellfish systems, cages, net pens, ocean ranching, and reservoir ranching, each of which will be described in much more detail further on.

Open systems are probably the oldest aquaculture systems. Early examples include the enhanced oyster systems of ancient Rome (fig. 4.1) and early examples of cage culture. Open systems (like all systems) have both positive and negative attributes. Because these systems use the natural environment to produce their crops, initial investments can be relatively low. It may be just a matter of releasing hatchery fish or shellfish, letting them grow for a period of time, and then

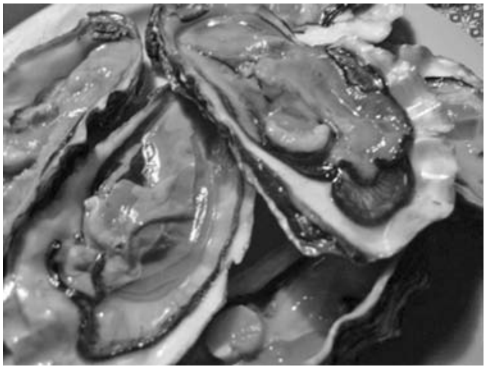

Figure 4.1 Oysters were raised or at least enhanced by the early Romans.

coming back and harvesting the crop. Therefore, management and input costs are also relatively low. However, the large water bodies needed for open system culture often involve public waters or waters that are surrounded by multiple land owners. This can bring up questions of ownership of the culture system and even ownership of the crop (Pillay & Kutty 2005). Many shellfish systems rely on leases from government entities, which can be strongly influenced by public opinion (where concerns may or may not be based on hard science). There is a strong suspicion, often fueled by sensationalist reporting, that all aquaculture systems are somehow polluting and harmful (De Silva & Soto 2009). A balanced review demonstrates that relative to the great majority of the other food commodities, the environmental impact of aquaculture is low (De Silva & Soto 2009). In fact, shellfish systems can actually be significant agents for positive environmental change by filtering out excess nutrients and productivity sourced from terrestrial livestock production, lawn fertilization, and other factors (Subasinghe 2007).

A negative of the low management inputs in aquaculture is that we also have little oversight or control. Poaching can be a problem. Many people feel they have every right to catch or harvest any aquatic animal from a natural or public body of water. For enforcement agencies responsible for public waters, ownership issues are often ill defined and oversight and enforcement responsibilities remain largely unresolved. The agencies with oversight over public waters are usually guided and empowered by environmental and wildlife regulations, not theft or livestock rustling statutes. Even if ownership is defined (by a lease agreement) who then has the right or obligation of enforcement—the owner or the public agency? I once visited a net-pen operation in Corsica. They kept an armed guard out on the water twenty-four hours a day, 365 days a year to protect their crop from poachers (fig. 4.2). You would have to consider this expense as a significant management input.

Poaching is not the only significant source of losses in open systems; predation can also be a problem. In the 1970s ocean ranching showed great promise as a method for producing salmon. However, in reality, losses during the two to three

Figure 4.2 Guarding sea cages from poachers.

years of ocean growth were so high that they made the method economically unfeasible (Arnason 2001). In shellfish systems constructed to get the animals up off the bottom, these steps are taken to get them away from predatory starfish and snails (such as the oyster drill), which cannot swim (Stickney 1979).

4.1.1 Bivalve culture: floats, trays, and rafts

Within the category of open systems we have a number of production methods. For bivalves these include floats, trays, and rafts. By placing the animals in the containers, these normally benthic animals can be suspended off of the bottom. This has the advantage of not only reducing predation (as previously mentioned), but also opening up all three dimensions of the water column to production. It also allows them to be suspended at depths where maximum phytoplankton (their primary food source) densities are found.

4.1.2 Cages and net pens

Cage culture is another open system production method. Cage culture is primarily used for finfish and occasionally for crustaceans. It basically represents a "fencing-off" of a portion of the natural aquatic habitat. Some cages are literally fenced compounds in shallow water. The bottom of the cage is the mud bottom of the bay or lake. In others, the cages have net bottoms and are suspended off of the bottom by flotation. These can be small cages (1 to 4 m^3) floating

in shallow freshwater ponds. Larger cages used in marine environments are usually referred to as net pens. They were initially used in protected waters such as fjords and bays. In recent years they have been scaled up to sizes of 20,000 to 40,000 and even 60,000 cubic meters and engineered to take the abuse of unprotected offshore waters. Some are now fully enclosed structures that can be moved if needed, or (as discussed later) may evolve self-powered mobility (Cohen 2009).

4.2 Semi-closed systems

Within this category we still rely largely on nature to provide the three basic ecological services of proper temperature, sufficient oxygen, and waste removal. However, within the semi-closed category the production units themselves are now largely manmade. Production methods within semi-closed systems include ponds and raceways. Within the production units we now have the ability to add or remove water. There is more management input in these systems, and the first steps toward supplementing or enhancing natural processes exist in these systems, as well.

In semi-closed systems water is taken from a natural source such as rainfall, springs, streams, or rivers. The water is then gravity-flowed or pumped into specially designed and constructed production units. The water can be used once and discharged or constantly cleaned and reoxygenated by natural processes. Compared to open systems, semi-closed systems have several advantages. One is much higher production rates, as much as 1,000 times the productivity of an open system. This is due to the greater control and inputs into these systems and the fact that their physical parameters can be maximized for greater productivity.

As an illustration, compared to a deep reservoir used for cage culture, an aquaculture pond is shallow, allowing it to warm quickly by the sun. This also reduces the possibility of turnover, as there is little thermal stratification. It is also easier to monitor dissolved oxygen levels and aerate if needed. Because of these factors, while open-system cage culture in a large pond or reservoir is normally limited to a maximum production of approximately 2,000 kg/ha, in a semi-closed system pond culture production is increased to greater than 5,000 kg/ha.

Advantages of semi-closed systems over open systems include easier and more efficient use of prepared feeds, control over water depth or water replacement, practical and cost-effective mechanical aeration, more easily controlled poaching and predation, elimination of competitors and predators, effective detection and rectification of water quality deterioration and diseases, and potential temperature control. However, there are also negatives. Construction and equipment costs can be significant, there are more management demands for monitoring and intervention, energy and feed inputs are higher, and there is a greater likelihood that water quality issues and diseases will occur.

Figure 4.3 A flow-through raceway. Photo courtesy of Charles Weibel.

4.2.1 Raceways

Raceways are basically large manmade earthen or concrete troughs (fig. 4.3). A typical length:width:depth ratio in linear raceways is 30:3:1 (Stickney 2009). High-quality water flows into and through the trough bringing in needed oxygen and flushing away wastes. Water sources are usually ground waters coming to the surface in the form of springs or surface water from snow melt or rain runoff from higher elevations. The water can often be reused several times as the water flows through multiple raceways in series. Inputs come in the form of high-quality feeds, simple aeration between raceways, cleaning of raceways, size grading of the animals, and easy observation of the fish for disease problems and efficient feed utilization. Raceway production is very intensive in terms of land use. On a per hectare basis, an excess of 300,000 kg of fish can be produced per year. However these systems require *a lot* of water. To produce 1 kg of trout in a raceway requires 98,000 liters of water, compared to 1,250 to 1,750 liters to produce a kg of catfish in a leveed pond (Fornshell & Hinshaw 2008). Because of this extremely high water demand (>1,500 Lpm), the siting of commercial raceway operations is almost completely dictated by availability of suitable water resources. A suitable source must provide sufficient volumes of water at correct temperatures constantly, year around.

In raceways the oxygen is provided by incoming water. It must come into the raceway saturated with oxygen. If ground water is used, it must be coming from unconfined underground spaces where it has been tightly exposed to air. If the water has been confined between strata, it can have low levels of oxygen and be supersaturated with certain undesirable gases.

Wastes produced in these systems are passed on for processing further downstream in the receiving waters, or onsite in designed treatment units. Temperatures in raceway systems reflect their water source. Retention time is low so temperature changes little within the system. Raceways using ground water have water temperatures the same as the region's groundwater, which is directly correlated to proximity to the equator. Exceptions include raceways utilizing surface waters or deep source geothermal waters. Raceways are covered in more detail in chapter 9.

4.2.2 Ponds

There are several types of ponds. The simplest and easiest to construct is a watershed or impoundment pond. These are constructed by building a dam across a natural waterway to retain the rain runoff at a level set by the dam. It is essential when building this dam that it be properly cored or keyed with an impermeable material to prevent seepage. They are usually triangular in shape (fig. 4.4) and can be relatively inexpensive to construct. However, it can be difficult to control how much water goes into a watershed pond during rain events. In areas with rolling topography, these ponds do not have consistent depths as they tend to be deep at the dam end and shallow on the far end. The pond's shape is largely dictated by the land's topography. This type of pond needs to be constructed with a proper water-control structure, such as a spillway or overflow pipe, to ensure that excess water can leave without cutting the dam. However, this also allows nutrients and even fish to be washed out of the production unit.

A pond specifically designed and built for aquaculture is usually a leveed pond (fig. 4.5). They commonly have a 2:1 length to width ratio. They can be efficiently

Figure 4.4 A watershed type pond. Photo courtesy of Charles Weibel.

Figure 4.5 Leveed style ponds used in catfish production.

constructed by "cut and fill." By this method if 1 meter of soil is excavated then moved to the perimeter of the planned pond and used there to build a levee, this 1-meter cut can result in 2 meters of water depth. By using this method, large ponds (>10 ha) can be constructed with relatively small construction equipment (i.e., tractors with dirt pans). These ponds are not normally constructed to depths deeper than 1.5 meters because (1) the cost of pond construction is the cost of moving dirt; and (2) shallow ponds tend to stay well mixed, reducing the chance of crop loss due to pond turnover.

The type of soil used for pond construction is important to minimize leakage. In general, clay content of ≥20% is desirable. If these conditions are not available, pond liners are widely available. However, for most applications in medium- to large-scale commercial aquaculture, they can be cost prohibitive. Ponds used in commercial aquaculture production vary widely in size. Ponds used in freshwater prawn production in the United States are often 0.1 to 0.2 ha in size while catfish production ponds are often ≥8 ha in size. In early years, catfish production ponds were sometimes built as large as 30 ha. In ponds, most of the oxygen budget is based on oxygen production by photosynthetic phytoplankton. In the past this was the limiting factor for production within these systems. Without supplemental feeding the carrying capacity of a pond is around 500 kg/ha. With supplemental feeding this can be increased to about 1,500 kg/ha. However, at this biomass density and the accompanying feeding rate of 30 to 40 kg/ha/day, the chance of low oxygen periods during the night or early morning starts to become unacceptably high (Boyd 1979). In most commercial-scale pond production systems man has intervened by providing mechanical aeration. With this change, feed rates can be increased to about 100 kg/ha/day and production can be increased over threefold to more than 4,500/kg/ha.

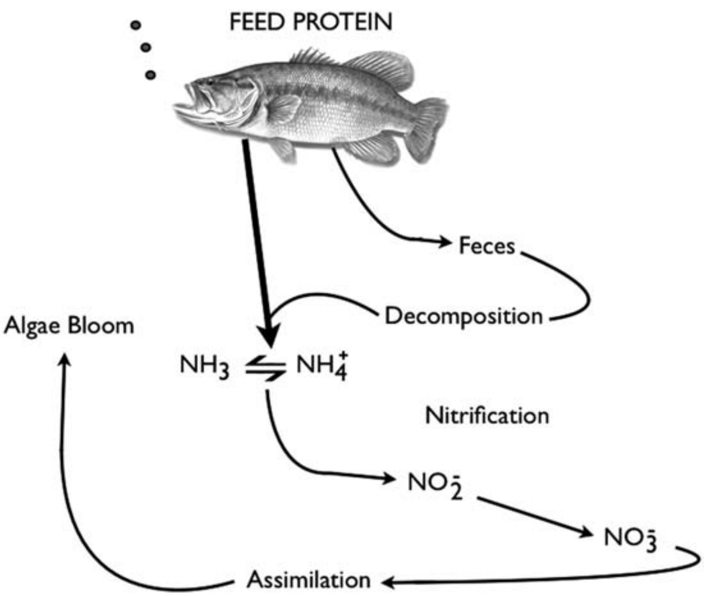

Figure 4.6 Nitrogen cycle in ponds.

Ponds still rely on natural processes to remove waste products. Again, solid wastes are broken down primarily by heterotrophic bacteria and detritivores on the pond bottom. Ammonia ($NH^+{}_4$) excreted by fish or shrimp is directly assimilated by algae or converted to less toxic nitrite ($NO^-{}_2$) by *Nitrosamonas* bacteria then on to nitrate ($NO^-{}_3$) by *Nitrobacter* bacteria. The nitrate form can then be assimilated by algae (fig. 4.6). The efficiency of this nitrogen removal system is now the primary bottleneck in further pond production intensification. Maybe man can again intervene by increasing the rate of algal assimilation (see Partitioned Aquaculture Systems, chapter 13) or by increasing the rate of bacterial nitrification. Pond systems are discussed more thoroughly in chapter 10.

Water temperatures in these systems are basically ambient. They lag behind, but reflect, the mean air temperature in the region. Near the equator there is little seasonal fluctuation. As you move further from the equator seasonal fluctuations become more pronounced and can either affect growth or even produce mortality. There has been some work in using waste heat from power plants and other industries to warm pond waters. However, fish production is usually a secondary consideration. The needs of the primary industry usually take priority and have created problems in the past during shut down for repairs or maintenance.

In ponds, a significant portion of the food for the culture organism can also be generated internally. If this is the primary food for the system it is said to be an extensive pond system. The natural carry capacity of an unfed pond is in the range of 250 kg/ha. This carrying capacity can be increased by adding nutrients to the system. In most extensive or low-input systems these nutrients are supplied

in the form agricultural byproducts, or animal (or human) waste. This is known as organic fertilization. If needed nutrients are supplied in their purely chemical form (often derived from petrochemicals) they are knows as inorganic fertilizers. Again, there are positives and negatives to each.

Positives of organic fertilizers include low costs, slow release of nutrients, and sustainability aspects of reuse. Negatives include the need to handle bulk and sometimes wet (and heavy) materials for small amounts of nutrients. To be made available to the phytoplankton and food web these materials must first be decomposed by microbes, which can be fairly slow and is an oxygen consuming process. These products can also directly deteriorate water quality (for example, by yielding ammonia) if misapplied. Inorganic fertilizers have the positive aspects of acting quickly, without deteriorating water quality through added nitrogenous wastes. However, inorganics can be more expensive and can actually work "too well" if misapplied. A slight over application of phosphorous can cause of a rapid phytoplankton bloom, which can die off just as rapidly. This can result in oxygen depletion as the phytoplankton decomposes.

4.3 Closed systems

In closed systems water is reused within a manmade culture system (fig. 4.7). Also, there is human intervention of some type and at some level in *all* of the basic processes. The major advantage of closed systems is that they provide the operator complete control over all of the environmental variables in the culture

Figure 4.7 A recirculating aquaculture system. Photo courtesy of the Conservation Fund's Freshwater Institute.

system. The major *disadvantage* of closed systems is that the operator now has complete *responsibility* for all aspects of the animals' environment.

In closed systems water temperature can be maintained very near the optimum growing temperature for the cultured animal. This can have a tremendous positive impact on not only growth rate but also efficiency, both of which are highly important in these systems. Because of this temperature control, we can now raise tropical animals in temperate zones, if that is where the markets are. Waste heat from industrial processes can provide economic advantages if the schedules and proximities of the systems are compatible.

With closed systems, water can be constantly disinfected with ultraviolet (UV) lights or ozone to crop down pathogenic organisms. Predators and poachers can be completely eliminated. External environmental events like floods or cold snaps are no longer a problem. Feed can be efficiently administered and consumption and conversion accurately monitored. Water supply volumes become less of a concern. However, for large systems, their loss of more than 5% of their total water volume per day (for maintenance reasons) can still become substantial.

4.3.1 Biofilter-based systems

Recirculating aquaculture systems (RAS) are also known as closed loop systems, recycle systems, and intensive recycle systems. As these names imply, as opposed to trout raceways that have a constant inflow of new water, these systems use the same water over and over. They do this by constantly adding air or oxygen to the water and removing the waste products produced by the fish. If aeration is used, production is limited to about 40 kg/m^3 (0.33 lb/gal). With the use of pure oxygen (oxygenation) production can be increased to approximately 120 kg/m^3 (1.0 lb/gal; Timmons *et al.* 2002). To remove waste products most systems rely on mechanical filters to remove solid wastes. Then, nitrogenous wastes such as ammonias are detoxified to nitrite and then nitrate, using the same nitrifying bacteria discussed regarding ponds. However, these bacteria are now cultured at very high densities inside containers known as biofilters. The nitrifying bacteria in the biofilter need a surface to attach to so special materials, known as media, are packed or suspended inside of the biofilter vessel to provide extra surface area for large numbers of bacteria to grow on. However, it is also important for the biofilter media to have sufficient open areas for the water to flow through and wash over the bacteria so that they can "consume" the inorganic waste and excrete less toxic versions.

4.3.2 Heterotrophic or biofloc-based systems

In recent years another type of closed or recycle system has been developed. Instead of relying on chemoautotrophic nitrifying bacteria, which utilize inorganic

compounds such as ammonia for energy, these systems are colonized with heterotrophic bacteria that consume the organic wastes. These bacteria are not confined in biofilters but live suspended in the culture vessel along with the animal being cultured. Once this bacterial population is established and stabilized, very high production rates can be achieved (>5 kg/m^3). However, these systems also have very high oxygen demand and relatively little research has been conducted on their complex microbial ecology. These systems can quickly remove nitrogenous waste products from the animals by directly converting it to bacterial biomass. In traditional RAS, quick removal of solids is important to their function. In heterotrophic or biofloc systems these solids are largely retained in the culture tanks and become colonized with heterotrophic bacteria, fungi, and protozoans into suspended particles called bioflocs. The bioflocs also recycle the wastes as they can be grazed by the animals and directly consumed as high-protein forage. Heterotrophic/biofloc systems are covered in more detail in chapter 12.

4.4 Hybrid systems

Many new approaches in recent years are blurring the lines between the different production systems and even major categories (open, semi-closed, and closed). They take aspects of different systems and combine them in new ways to overcome the shortcomings of one, capitalize on the positives of another, or break a system into its functional components so they can be individually manipulated.

4.4.1 Aquaponics

In a system called aquaponics, the basic components of a recirculating system are utilized. However, the biofilter has been replaced by plants that assimilate the nitrogenous waste products and then turn it into saleable plant products (fig. 4.8). Aquaponics systems are increasingly of interest in areas where water availability is limited. Much of their early development has occurred on small islands where the supply of fresh fish, freshwater, and fresh vegetables are all limited. There is increasing interest in evaluating these systems in arid countries, such as those in the Middle East. Now there are also efforts to apply these technologies to generating fresh fish and vegetables in or near major urban areas. These are meant to address the phenomenon known as "food deserts." These are urban areas where city dwellers do not have ready access to healthy foods at reasonable prices (Ford & Dzewaltowski 2008). This makes these populations, especially certain ethnic groups, even more susceptible to health problems such as type 2 diabetes and obesity. Urban aquaponics might represent an "oasis" of healthy foods in or near the food deserts.

Figure 4.8 An aquaponics system at the University of the Virgin Islands.

4.4.2 In-pond raceways

In-pond raceways are similar to cages floating in open system waters or semi-closed system ponds. However, they take on the characteristics of a raceway by constantly flowing water through cages by mechanical means. In-pond raceways allow the fish to be confined in small systems so they can be more efficiently fed and monitored (like a raceway). They also give at least the potential of capturing waste products for removal, again like a raceway. However, unlike regular raceways, these systems are not confined to locations with large groundwater springs or flowing surface water resources. These "raceways" can be located wherever large ponds or reservoirs exist. The temperature and waste removal functions of these systems are still handled by the same pond processes. The oxygen needs of these systems are also primarily addressed by the pond system. However, since the fish are confined at much higher densities, dissolved oxygen supplies are usually supplemented by mechanical aeration, and at times by addition of pure oxygen. This system is covered in more detail in chapter 15.

4.4.3 Partitioned aquaculture system

With the partitioned aquaculture system (PAS), the concept of a pond as an algae-driven system is modified to address one of a traditional pond's limiting factors. In heavily fed ponds dense plankton blooms develop and light cannot

penetrate deeply, so only the upper level of the water column is fully functional (i.e., has sufficient light for photosynthesis). By taking the water and circulating it through channels that are only 40 to 60 cm deep, essentially all of the water volume gets sufficient sunlight to be productive, allowing threefold to fourfold production increases in the same area and volume. The PAS system is covered in more detail in chapter 13.

The PAS is not so much a hybrid system as it is a "deconstruction" of a pond-based system into its functional components so that each component can be modeled and its efficiency maximized. It is still basically a pond system. However, the primary culture fish are now confined in a cage similar to an in-pond raceway. Again, there is at least the potential of removing solid wastes from the system. Water is moved very efficiently using low rpm hydraulic paddlewheels that push the water out into the shallow channels. The combination of water movement and shallow water depths results in conditions where light penetration is no longer a limiting factor and algae fixation rates are no longer light limited. To keep algal cells in a rapid growth phase, and again maximize their efficiency, an algae grazing fish is confined in another cage within the water flow. Their feeding crops the algae, keeping cell age down and their metabolism (and oxygen production and ammonia removal) high.

As you can see, aquaculture is an extremely diverse enterprise not only in the number of species we raise, but also in how we raise them. While some methods are millennia old, some are only a few decades old at most. As the demands placed on aquaculture continue to increase, there will undoubtedly continue to be changes in the way we raise aquaculture species. Some of these changes will be revolutionary. Most will be evolutionary. However, change and improvement *is* inevitable.

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